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The Nuclear Shell Model Toward the Drip Lines

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Abstract.

We describe the "islands of inversion" that occur when approaching the neutron drip line around the magic numbers N=20, N=28 and N=40 in the framework of the Interacting Shell Model in very large valence spaces. We explain these configuration inversions (and the associated shape transitions) as the result of the competition between the spherical mean field (monopole) which favors magicity and the correlations (multipole) which favor deformed intruder states. We also show that the N=20 and N=28 islands are in reallity a single one, which for the Magnesium isotopes is limited by N=18 and N=32.

1. Monopole anomalies and Multipole universality

The different facets of the nuclear dynamics depend on the balance of the two main components of the nuclear hamiltonian; the Monopole which produces the effective spherical mean field and the Multipole responsible for the correlations [1]. Large scale shell model calculations have unveiled the monopole anomalies of the two-body realistic interactions, *i.e* that they tend to produce effective single particle energies which are not compatible with the experimental data and which, if used without modifications, produce spectroscopic catastrophes. Already in the late 70's Pasquini and Zuker [2] showed that the Kuo Brown [3] interaction could not produce neither a magic ^{48}Ca nor a magic ^{56}Ni. In this last case it made a nearly perfect rotor instead. A few monopole corrections (mainly T=1) restored high quality spectroscopy. Otsuka *et al.* [4] have recently shown that the monopole component of the three body force may explain the monopole anomalies relevant for ^{28}O and ^{48}Ca. The Multipole component of the realistic two body interactions (dominated by L=0 pairings, quadrupole and octupole) does not seem to require any substantial modification and it is "universal" in the sense that all the interactions produce equivalent multipole hamiltonians. Magic numbers are associated to energy gaps in the spherical mean field. Therefore, to promote particles above the Fermi level costs energy. However, in some cases intruder configurations can compensate their loss of monopole energy with their huge gain in correlation energy. Several examples of this phenomenon exist in stable magic nuclei in the form of coexisting spherical, deformed and superdeformed states in a very narrow energy range, providing examples of nuclear allotropy. In the case of ^{40}Ca they can be described in the spherical shell model framework [5].

2. The islands of inversion at N=20 and N=28 far from stability

The region around ^{31}Na provides a beautiful example of intruder dominance in the ground states, known experimentally since long [6, 7]. Early shell model calculations (Poves and Retamosa [8], Warburton, Becker and Brown [9]) unveiled the role of deformed intruder configurations, 2p-2h neutron excitations from the *sd* to the *pf*-shell, and started the study of the boundaries of the so called "island of inversion" and the properties of its inhabitants. Similar mechanisms produce the other known "islands of inversion" centered in ^{11}Li (N=8), ^{42}Si (N=28), and ^{64}Cr (N=40). We propose now an unified description of the nuclei between Oxygen and Calcium, covering in many cases all the isotopes between the neutron and proton drip lines. The valence space comprises two major shells; the *sd*-shell ($0d_{5/2}$, $1s_{1/2}$, $0d_{3/2}$) and the *pf*-shell ($0f_{7/2}$, $1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$) and the effective interaction is SDPF-U [10].

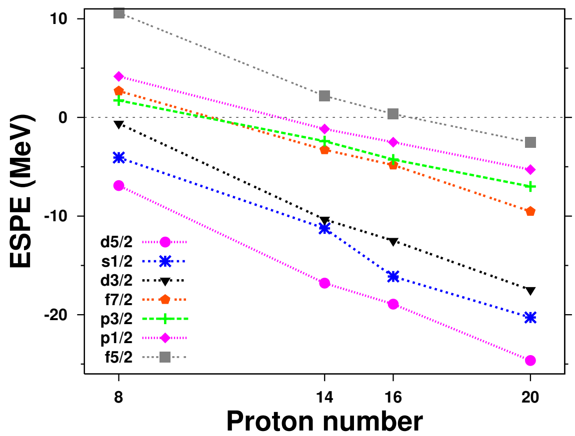

Figure 1. Neutron effective single particle energies (ESPE) for the N=20 isotones computed with the SDPF-U interaction

N=20: Four protons away from doubly magic ^{40}Ca, ^{34}Si is a new doubly magic nucleus because the proton Z=14 and the neutron N=20 gaps reinforce each other. To go even more neutron rich, one needs to remove protons from the $0d_{5/2}$ orbit. This causes two effects; a reduction of the N=20 neutron gap (see Fig. 1) and the increase of proton collectivity. Both conspire in the sudden appearance of an Island of Inversion in which Deformed Intruder states become ground states, as in ^{32}Mg, ^{31}Na and ^{30}Ne.

N=28: As we remove protons from doubly magic ^{48}Ca, the N=28 neutron gap slowly shrinks. In ^{46}Ar the collectivity induced by the action of the four valence protons in the nearly degenerate quasi-spin doublet $1s_{1/2}$-$0d_{3/2}$, is not enough to beat the N=28 closure. ^{46}Ar is non-collective. In ^{44}S, the quadrupole collectivity sets in. The N=28 closure blows out and prolate and non collective states coexist. The ground state and the first excited 2^+ form the germ of a prolate rotational band. In turn ^{42}Si is an oblate, well deformed, rotor with a first 2^+ state at 770 keV [11] and ^{40}Mg is predicted to be a very collective prolate rotor, with a 2^+ at $\sim$720 keV. In addition it could well develop a neutron halo because more than two neutrons are, in average, in *p* wave.

In the left panel of Fig. 2 we compare the experimental 2^+ excitation energies of the even Mg isotopes with the shell model calculations with the SDPF-U interaction. Up to N=16 the calculations are restricted to the *sd*-shell and therefore the results are the same than the ones produced by the USD interaction [12]. Beyond N=16 the calculations include up to 6p-6h excitations from the *sd*-shell to the full *pf*. The agreement is excellent and covers all the span of isotopes from the proton to the neutron drip line. Notice the disappearance of the semi-magic

closures at N=20 and N=28 and the presence of a large region of deformation which connects the two islands of inversion, previously though to be split apart. In the left panel we compare the B(E2)'s in the transition region with some very new experimental data from Riken. The agreement is very good as well.

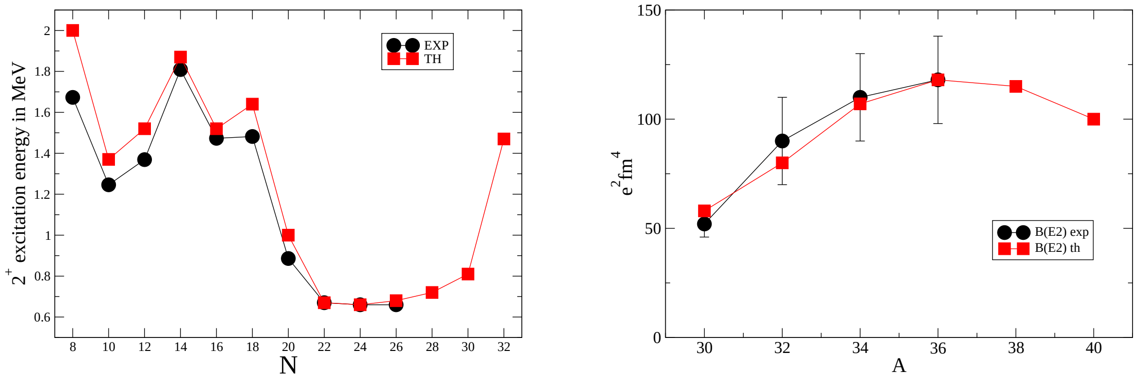

Figure 2. Comparison between the theoretical and experimental 2^+ excitation energies of the even Mg isotopes (left panel) and B(E2)'s (right panel). In the proton rich side some experimental energies are taken from their mirror nuclei.

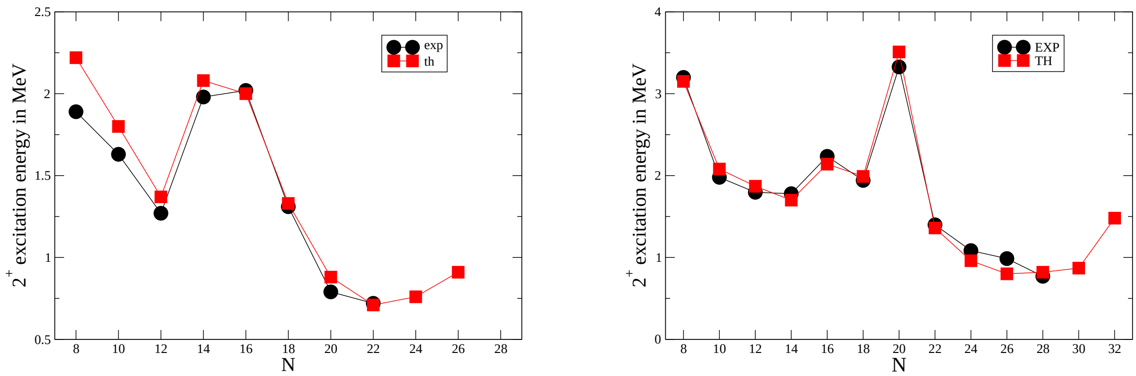

Figure 3. Comparison between the theoretical and experimental 2^+ excitation energies of the even Ne isotopes (left panel) and the even Si isotopes (right panel).

The results for the Neon isotopes (left panel of Fig. 3) are very similar to the Magnesiums. In the right panel we show the results for the Silicon isotopes (notice the very different energy scale). At variance with the Magnesium case, we observe a majestic peak at N=20, fingerprint of the double magic nature of ^{34}Si discussed above and, as in the Ne and Mg cases, no trace of the N=28 shell closure is seen.

3. The island of deformation south of ^{68}Ni

The situation at N=40 is similar to the one found at N=20 except that ^{68}Ni is not a "bona fide" magic nucleus. Removing protons from the $0f_{7/2}$ orbit, activates the quadrupole collectivity, which, in turn, favors the np-nh neutron configurations across N=40, which take advantage of the quasi-SU3 coherence of the doublet $0g_{9/2}$- $1d_{5/2}$. Large scale SM calculations in the valence space of the full *pf*-shell for the protons and the $0f_{5/2}$ $1p_{3/2}$ $1p_{1/2}$ $0g_{9/2}$ and $1d_{5/2}$ orbits for the neutrons, predict a new region of deformation centered at ^{64}Cr. In Fig. 4 we show our results for the N=40 isotones: The inversion of configurations sets in very rapidly when we remove protons from ^{68}Ni, and persists all the way down to ^{60}Ca even in absence of deformation. This shows that the island of inversion and the island of deformation may not cover the same territory. More details on these calculation can be found in ref. [13].

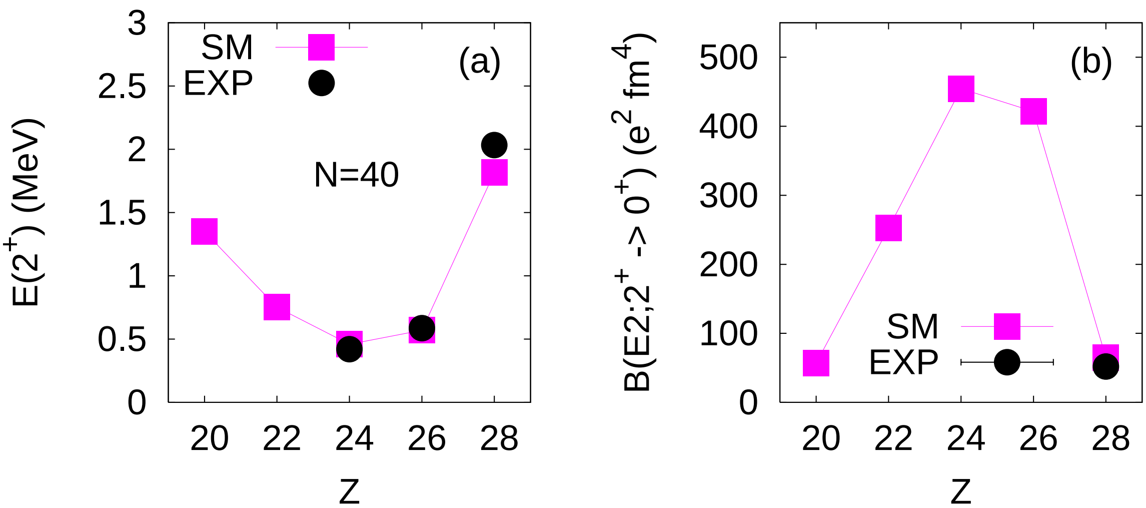

Figure 4. The N=40 isotones; comparison between the theoretical and experimental 2^+ excitation energies (left panel) and B(E2)'s (right panel)

Acknowledgments

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